Natural SUSY On Trial: Status of Higgsino Searches at ATLAS

Julia Gonski

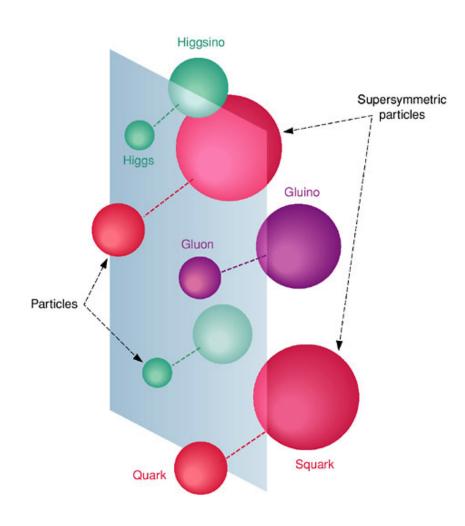
Harvard University

25 October 2018
US LHC User's Association
Annual Meeting



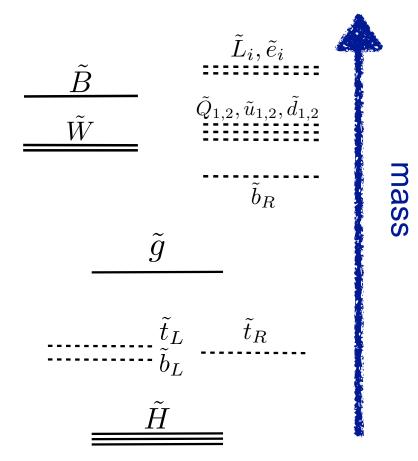
SUSY (The Defendant)

- Provides unification of forces, dark matter candidate, and solution to hierarchy problem
- Higgs mass quadratic corrections cancelled by new supersymmetric partners; higgsinos, stops and gluinos especially influential
- → What do we search for first?



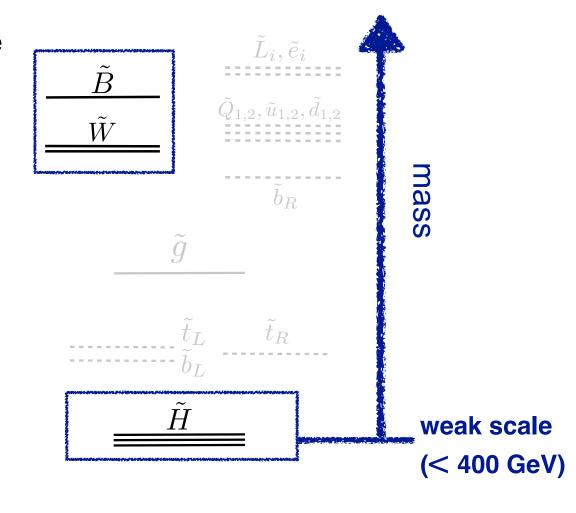
(if we got to pick)

 Naturalness = reduce fine tuning ⇒ 10%



(if we got to pick)

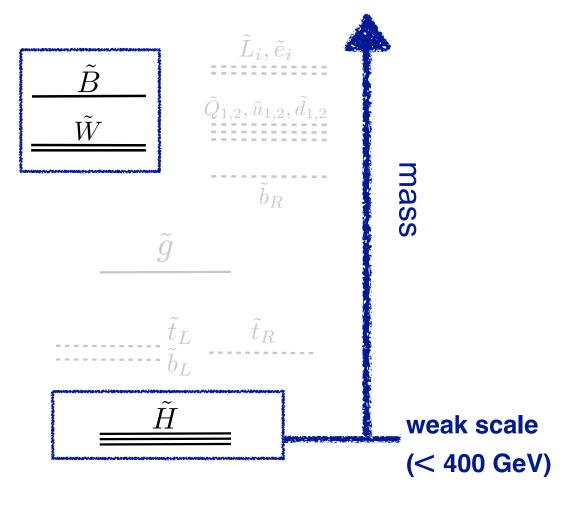
 Naturalness = reduce fine tuning ⇒ 10%



(if we got to pick)

 Naturalness = reduce fine tuning ⇒ 10%

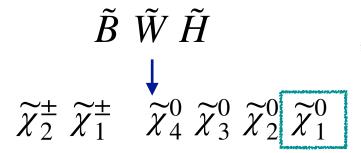
$$\begin{array}{cccc} \widetilde{B} & \widetilde{W} & \widetilde{H} \\ & \downarrow & \\ \widetilde{\chi}_{2}^{\pm} & \widetilde{\chi}_{1}^{\pm} & \widetilde{\chi}_{4}^{0} & \widetilde{\chi}_{3}^{0} & \widetilde{\chi}_{2}^{0} & \widetilde{\chi}_{1}^{0} \end{array}$$



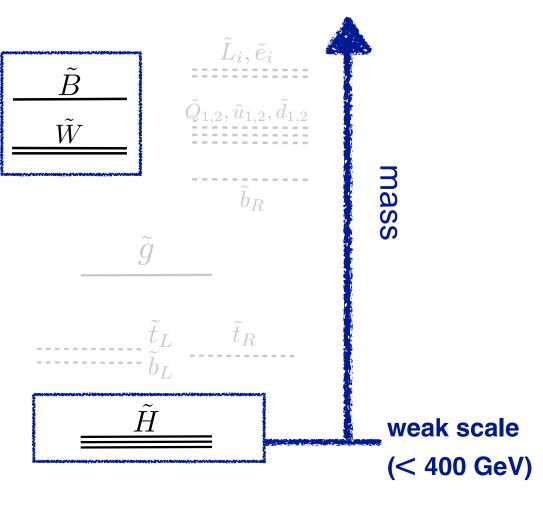
5

(if we got to pick)

 Naturalness = reduce fine tuning ⇒ 10%

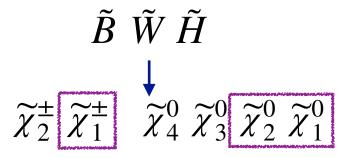


Dark matter candidate!
 Dominantly (but not purely)
 higgsino

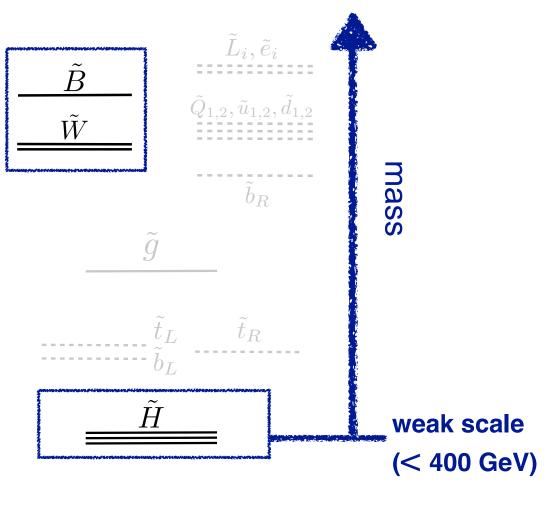


(if we got to pick)

 Naturalness = reduce fine tuning ⇒ 10%

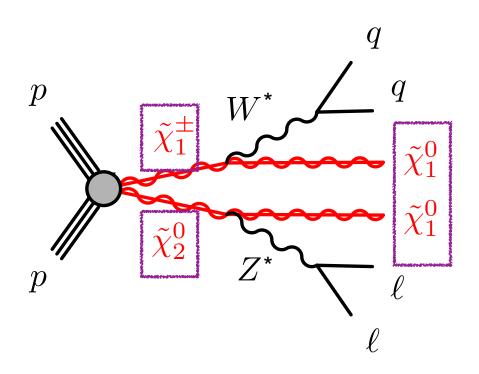


- Dark matter candidate!
 Dominantly (but not purely)
 higgsino
- Lightest three ewkinos are compressed (Δm ~ few GeV)



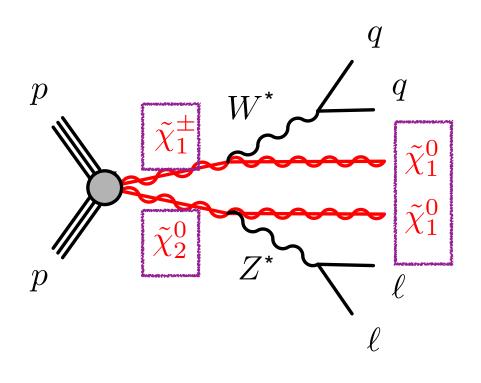
Higgsino Searches at ATLAS

Final state: 2
 opposite sign same
 flavor soft leptons



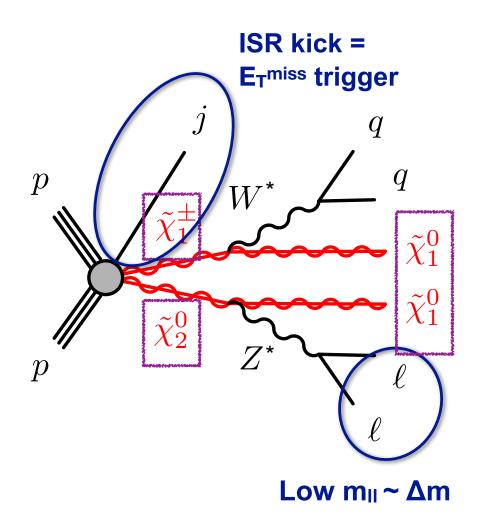
Higgsino Searches at ATLAS

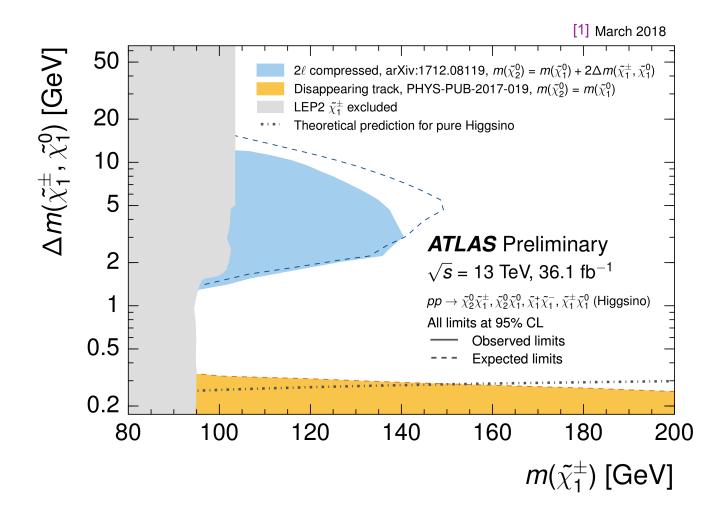
- Final state: 2
 opposite sign same
 flavor soft leptons
- Challenging!
 - Low production cross section
 - Small ∆m → low E_Tmiss, very soft leptons



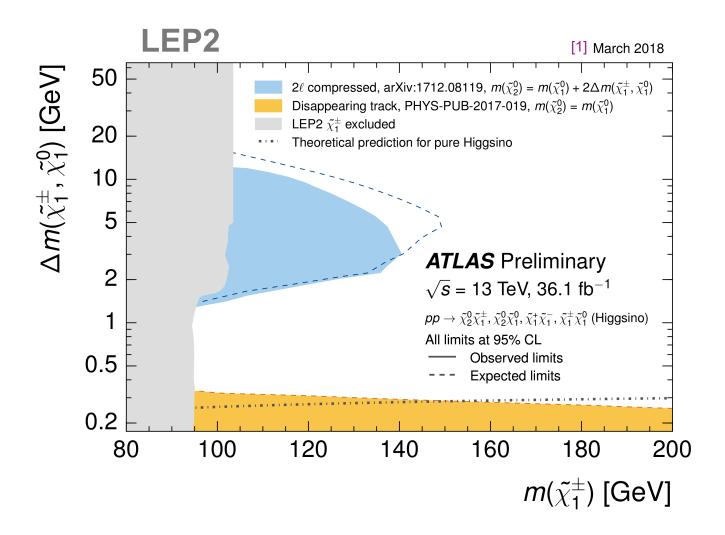
Higgsino Searches at ATLAS

- Final state: 2
 opposite sign same
 flavor soft leptons
- Challenging!
 - Low production cross section
 - Small ∆m → low E_T^{miss}, very soft leptons

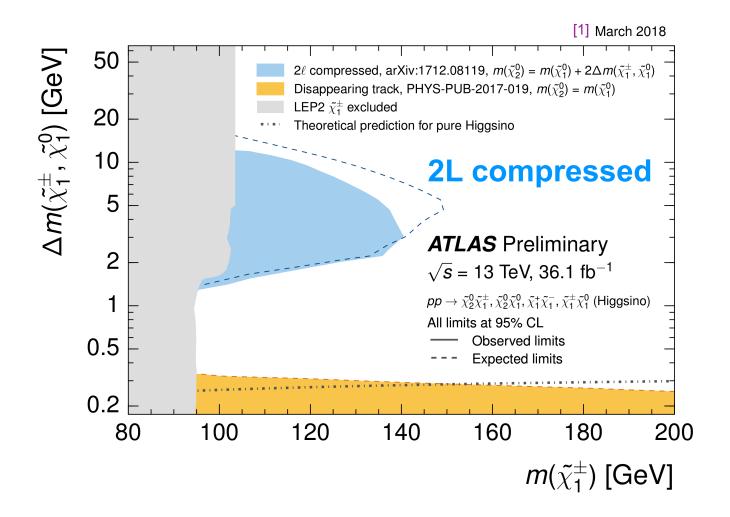




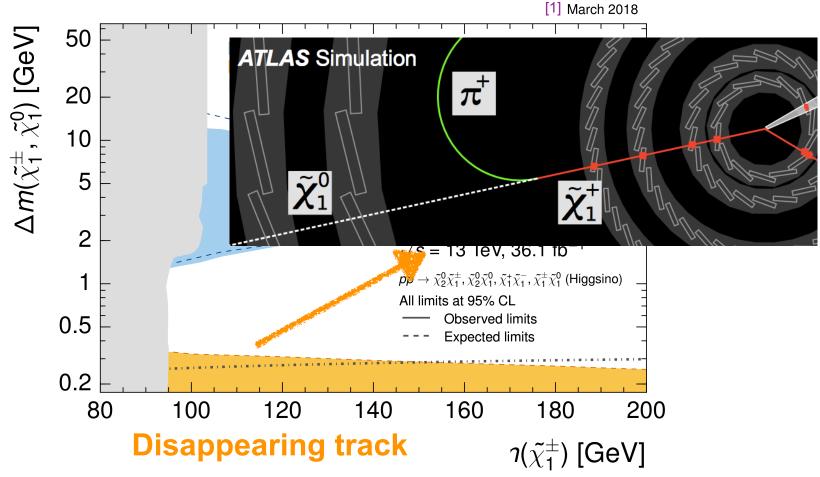
[1] ATLASSummaryPlots



[1] ATLASSummaryPlots

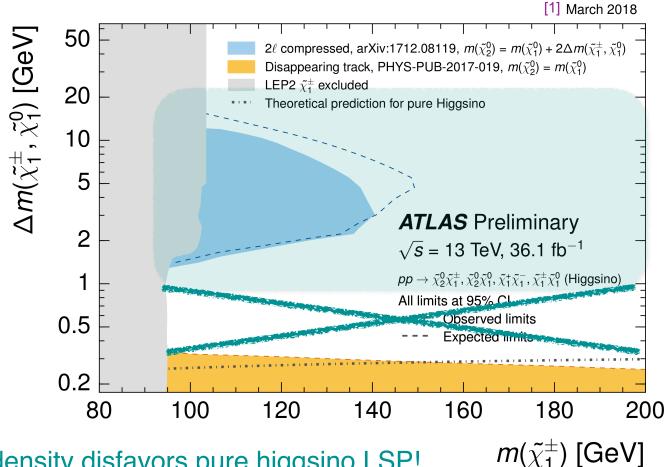


[1] ATLASSummaryPlots



Pure higgsino/wino state: Δm~100 MeV ⇒ long lifetime ~10⁻¹¹s [2]

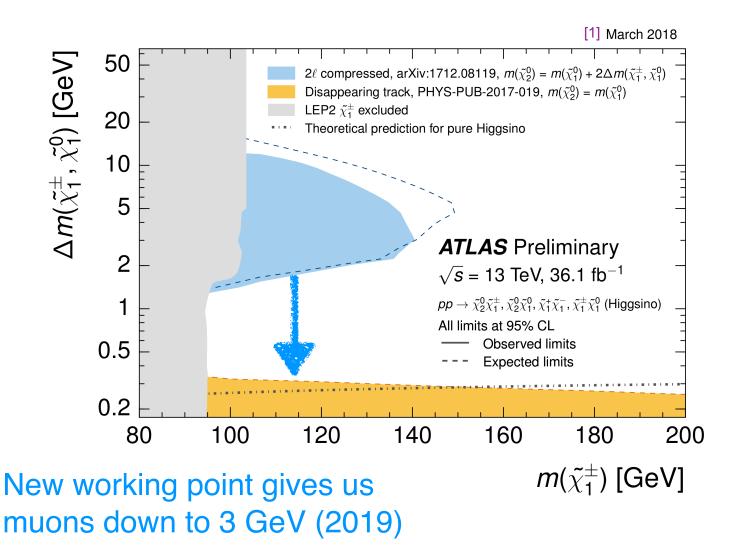
[2] ATL-PHYS-PUB-2017-19 [1] ATLASSummaryPlots



Relic density disfavors pure higgsino LSP! (Well-Tempered Neutralino) [3]

[3] <u>arXiv:0601041</u>

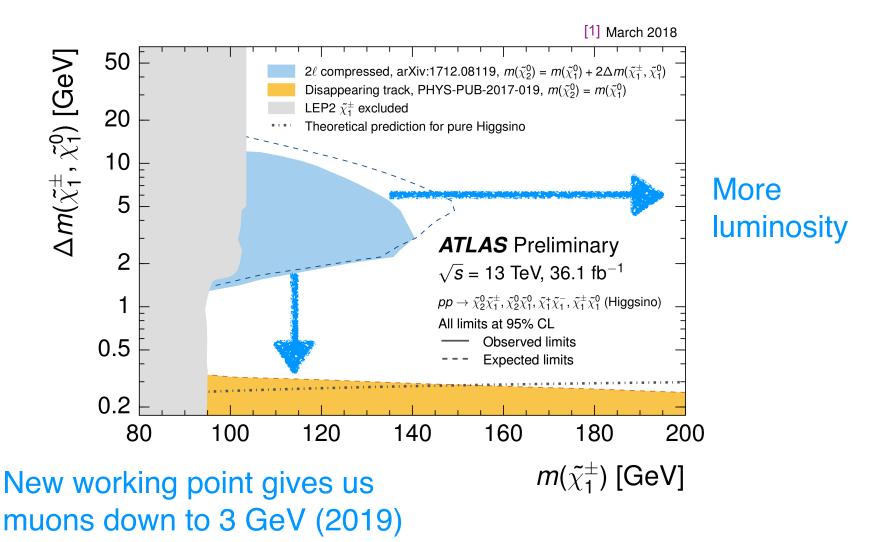
Areas of Improvement



[1] ATLASSummaryPlots

25 October 2018 J. Gonski 16

Areas of Improvement

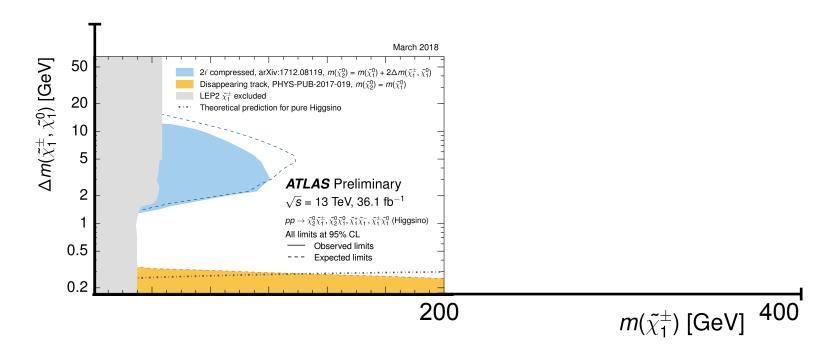


[1] ATLASSummaryPlots

25 October 2018 J. Gonski 17

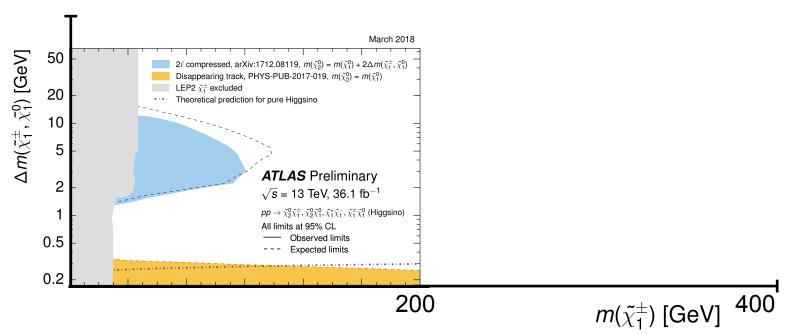
What's Next?

 Natural SUSY is still well-motivated! (& experimental constraints are weakest in the electroweak sector)



What's Next?

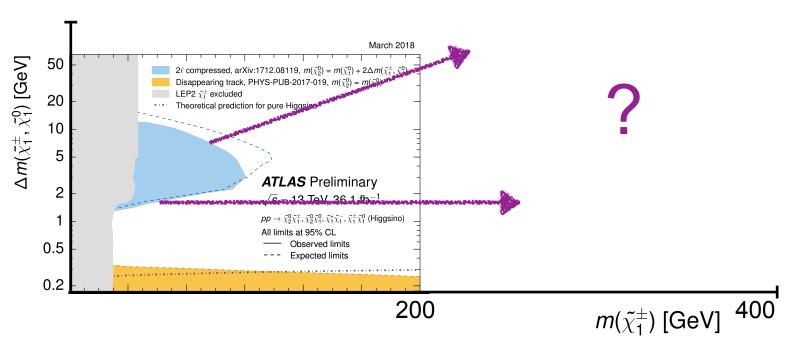
- Natural SUSY is still well-motivated! (& experimental constraints are weakest in the electroweak sector)
 - Fine tuning < 10% possible for m(\tilde{g}) < 2.5 TeV and m(\tilde{t}) < 1.5 TeV [4]



[4] arXiv:1611.05873

What's Next?

- Natural SUSY is still well-motivated! (& experimental constraints are weakest in the electroweak sector)
 - Fine tuning < 10% possible for m(\tilde{g}) < 2.5 TeV and m(\tilde{t}) < 1.5 TeV [4]
- Up next: softer leptons, 1L + track, HL-LHC! (2026+)

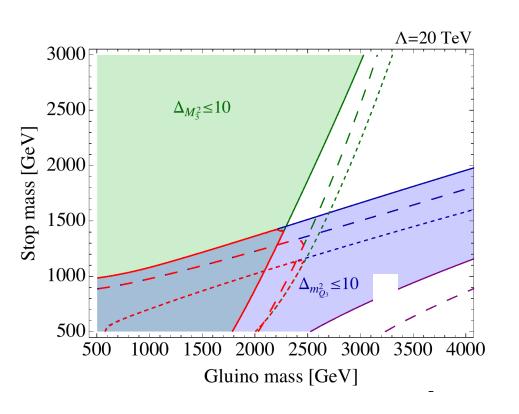


[4] arXiv:1611.05873

Backup

Precision Corrections to Fine Tuning

Buckley, Monteux, Shih arXiv:1611.05873



$$m_H^2 = m_{H,bare}^2 + \Delta m^2 - \Delta m^2$$

$$\Delta m^2 = |\mu|^2 \text{ (at tree level)}$$

$$\Delta \equiv \frac{2\delta m_H^2}{m_h^2} \le 10$$

$$\mu \le 400 GeV$$

Why Quasi-Degenerate?

Depends on neutrino mass matrix in MSSM! Using $(\widetilde{B}^0, \widetilde{W}^0, \psi_d^0, \psi_u^0)$ basis

$$M_{\tilde{N}^{0}} = \begin{pmatrix} M_{1} & 0 & -m_{W}t_{\theta_{W}}c_{\beta} & m_{W}t_{\theta_{W}}s_{\beta} \\ 0 & M_{2} & m_{W}c_{\beta} & -m_{W}s_{\beta} \\ -m_{W}t_{\theta_{W}}c_{\beta} & m_{W}c_{\beta} & 0 & -\mu \\ m_{W}t_{\theta_{W}}s_{\beta} & -m_{W}s_{\beta} & -\mu & 0 \end{pmatrix} \qquad M_{\tilde{C}} = \begin{pmatrix} M_{2} & \sqrt{2}s_{\beta}m_{W} \\ \sqrt{2}c_{\beta}m_{W} & \mu \end{pmatrix}$$



$$\left| m_{\chi_1^{\pm}} \right| - \left| m_{\chi_1^{0}} \right| \approx \frac{m_W^2 (1 \mp s_{2\beta})}{2(M_2 + |\mu|)}$$

$$\left| m_{\chi_2^{0}} \right| - \left| m_{\chi_1^{\pm}} \right| \approx \frac{m_W^2 (1 \pm s_{2\beta})}{2(M_2 - |\mu|)}, \quad \left| m_{\chi_2^{0}} \right| - \left| m_{\chi_1^{0}} \right| \approx \frac{m_W^2 (\pm |\mu| s_{2\beta} + M_2)}{(M_2^2 - |\mu|^2)}$$

Wino/bino as lightest electroweakino, # light states is different!

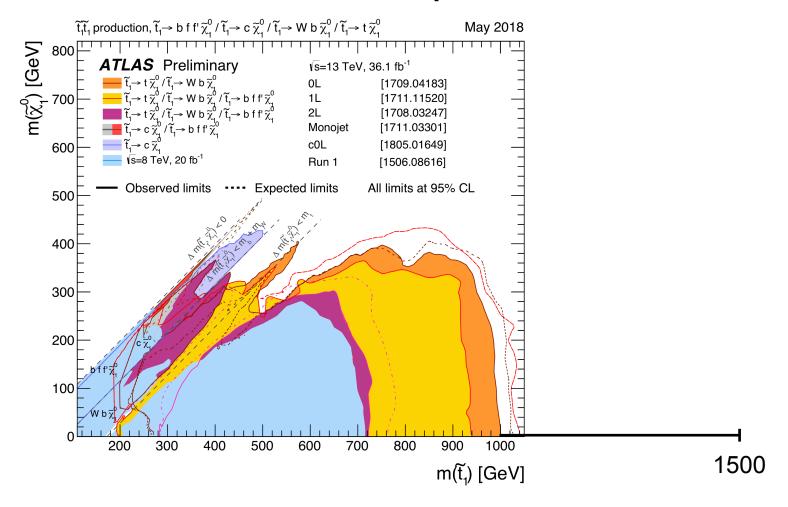
- · one neutral state for a light bino;
- one neutral and one charged state for a light wino.

arXiv:1401.1235

25 October 2018 J. Gonski 23

But we haven't found anything yet!

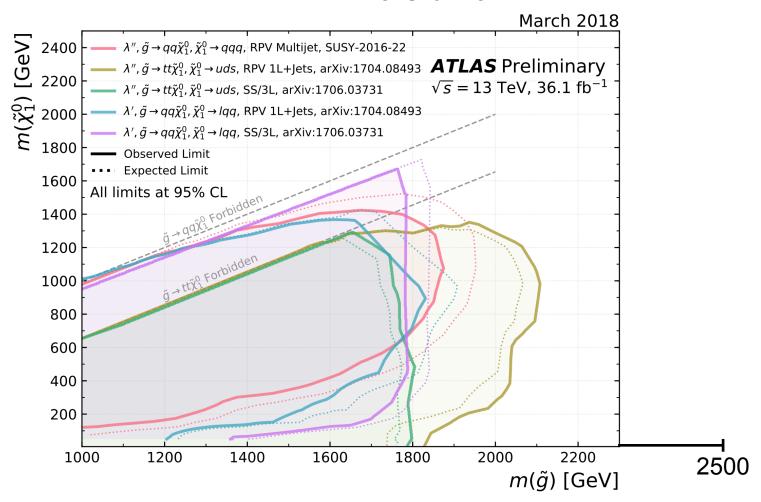
The Stop



Limits up-to ~1 TeV in stop mass ... but no limits if m(LSP) ≥ 400 GeV

But we haven't found anything yet!

The Gluino



ATLAS SUSY Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary

 $\sqrt{s} = 7.8.13 \text{ Te}$

00	Model	e,μ, au,γ	Jets	$E_{ m T}^{ m miss}$	∫£ dt[fb	⁻¹] Mas	s limit		$\sqrt{s}=7,$	$\frac{3 \text{ TeV}}{\sqrt{s}} = 13 \text{ TeV}$	$\sqrt{s} = 7, 8, 13 \text{ Te}$ \ Reference
S	$\tilde{q} ilde{q}, ilde{q}\! ightarrow\!q\! ilde{\chi}_{1}^{0}$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	 q̃ [2x, 8x Degen.] q̃ [1x, 8x Degen.] 	0.43	0.9	1.55	$m(ar{\chi}_1^0)$ <100 GeV $m(ar{q})$ - $m(ar{\chi}_1^0)$ =5 GeV	1712.02332 1711.03301
arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	ğ ğ		Forbidden	2.0 0.95-1.6	$m(\tilde{\chi}_1^0)$ <200 GeV $m(\tilde{\chi}_1^0)$ =900 GeV	1712.02332 1712.02332
e Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_{\perp}^{0}$	3 e, μ ee, μμ	4 jets 2 jets	- Yes	36.1 36.1	\tilde{g} \tilde{g}			1.85	$m(\tilde{\chi}_{1}^{0})$ <800 GeV $m(\tilde{g})$ - $m(\tilde{\chi}_{1}^{0})$ =50 GeV	1706.03731 1805.11381
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	$\overset{0}{\text{3 }e,\mu}$	7-11 jets 4 jets	Yes -	36.1 36.1	\tilde{g} \tilde{g}		0.98	1.8	$m(\tilde{\chi}_{\perp}^{0})$ <400 GeV $m(\tilde{g})$ - $m(\tilde{\chi}_{\perp}^{0})$ =200 GeV	1708.02794 1706.03731
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{t} \tilde{\chi}_1^0$	0-1 e, μ 3 e, μ	3 <i>b</i> 4 jets	Yes -	36.1 36.1	$ ilde{ ilde{g}} ilde{ ilde{g}}$			2.0 1.25	$m(\tilde{\chi}_1^0)$ <200 GeV $m(\tilde{g})$ - $m(\tilde{\chi}_1^0)$ =300 GeV	1711.01901 1706.03731
3 rd gen. squarks direct production	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 {\rightarrow} b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$		Multiple Multiple Multiple		36.1 36.1 36.1	$egin{array}{cccc} ilde{b}_1 & Forbidden & & & & & & & & & & & & & & & & & & &$	Forbidden Forbidden	0.9 0.58-0.82 0.7	m(ž	$\begin{array}{c} \text{m}(\bar{\chi}_{1}^{0}){=}300\text{GeV, BR}(b\bar{\chi}_{1}^{0}){=}1\\ \text{m}(\bar{\chi}_{1}^{0}){=}300\text{GeV, BR}(b\bar{\chi}_{1}^{0}){=}\text{BR}(t\bar{\chi}_{1}^{\pm}){=}0.5\\ \text{n}){=}200\text{GeV, m}(\bar{\chi}_{1}^{\pm}){=}300\text{GeV, BR}(t\bar{\chi}_{1}^{\pm}){=}1 \end{array}$	1708.09266, 1711.03301 1708.09266 1706.03731
	$\tilde{b}_1\tilde{b}_1,\tilde{t}_1\tilde{t}_1,M_2=2\times M_1$		Multiple Multiple		36.1 36.1	$egin{array}{ccc} ilde{t}_1 & & & & & \\ ilde{t}_1 & & & & & & & \\ \end{array}$		0.7		$m(\tilde{\chi}_1^0)$ =60 GeV $m(\tilde{\chi}_1^0)$ =200 GeV	1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}^0_1 \text{ or } t\tilde{\chi}^0_1$ $\tilde{t}_1 \tilde{t}_1, \tilde{H} \text{ LSP}$	0-2 <i>e</i> , <i>µ</i> 0	0-2 jets/1-2 Multiple Multiple	b Yes	36.1 36.1 36.1	$egin{array}{cccc} ar{t}_1 & & & & & & \\ ar{t}_1 & & & & & & & \\ ar{t}_1 & & & & & & & & \\ \end{array}$		0.4-0.9 0.6-0.8	m(/ m(/	$m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ $\tilde{\chi}_{1}^{0})=150 \text{ GeV}, m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}, \tilde{\iota}_{1} \approx \tilde{\iota}_{L}$ $\tilde{\iota}_{1}^{0})=300 \text{ GeV}, m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}, \tilde{\iota}_{1} \approx \tilde{\iota}_{L}$	1506.08616, 1709.04183, 1711.11520 1709.04183, 1711.11520 1709.04183, 1711.11520
3rd g direc	$ ilde{t}_1 ilde{t}_1$, Well-Tempered LSP $ ilde{t}_1 ilde{t}_1$, $ ilde{t}_1{ ightarrow}c ilde{\chi}_1^0$ / $ ilde{c} ilde{c}$, $ ilde{c}{ ightarrow}c ilde{\chi}_1^0$	0	Multiple 2c mono-jet	Yes	36.1 36.1 36.1	\vec{\tilde{\tilde{t}}_1}{\vec{t}_1} \\ \vec{\tilde{t}}_1 \\ \vec{\tilde{t}}_2 \\ \vec{\tilde{t}}_3 \\ \vec{\tilde{t}}_2 \\ \vec{\tilde{t}}_3 \\ \vec{\tilde{t}}_4 \\ \vec{\tilde{t}}_5 \\ \tilde	0.46 0.43	0.48-0.84 0.85	m(/	${\bf m}_{1}^{(0)} = 150 {\rm GeV}, {\bf m}(\tilde{\chi}_{1}^{\pm}) - {\bf m}(\tilde{\chi}_{1}^{0}) = 5 {\rm GeV}, \tilde{t}_{1} \approx \tilde{t}_{L} \\ {\bf m}(\tilde{t}_{1}^{0}) = 0 {\rm GeV} \\ {\bf m}(\tilde{t}_{1}, \tilde{c}) - {\bf m}(\tilde{\chi}_{1}^{0}) = 50 {\rm GeV} \\ {\bf m}(\tilde{t}_{1}, \tilde{c}) - {\bf m}(\tilde{\chi}_{1}^{0}) = 5 {\rm GeV} \\ \end{array}$	1709.04183, 1711.11520 1805.01649 1805.01649 1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 <i>e</i> , μ	4 <i>b</i>	Yes Yes	36.1	$ ilde{t}_1$ $ ilde{t}_2$	0.43	0.32-0.88		$m(\tilde{t}_1,c)$ - $m(\tilde{t}_1)$ =5 GeV $m(\tilde{\chi}_1^0)$ =0 GeV, $m(\tilde{t}_1)$ - $m(\tilde{\chi}_1^0)$ = 180 GeV	1706.03986
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	Yes Yes	36.1 36.1	$ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{0}^{0} $ $ \tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{2}^{0} $ 0.17	(0.6		$m(\tilde{\chi}_{\perp}^{\pm})=0$ $m(\tilde{\chi}_{\perp}^{\pm})=m(\tilde{\chi}_{\perp}^{0})=10 \text{ GeV}$	1403.5294, 1806.02293 1712.08119
EW direct	$ \begin{array}{l} \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \text{ via } Wh \\ \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^{+} {\to} \tilde{\tau} \nu(\tau \tilde{\nu}), \tilde{\chi}_2^0 {\to} \tilde{\tau} \tau(\nu \tilde{\nu}) \end{array} $	<i>ℓℓ/ℓγγ/ℓbb</i> 2 τ	-	Yes Yes	20.3 36.1	$\begin{array}{cccccccccccccccccccccccccccccccccccc$		0.76	$m(ilde{\mathcal{K}}_1^\pm)$ - m	$m(\bar{\chi}_{1}^{0})=0$ $m(\bar{\chi}_{1}^{0})=0$ $m(\bar{\chi}_{1}^{0})=0$, $m(\bar{\tau},\bar{\nu})=0.5(m(\bar{\chi}_{1}^{\pm})+m(\bar{\chi}_{1}^{0}))$ $(\bar{\chi}_{1}^{0})=100$ GeV, $m(\bar{\tau},\bar{\nu})=0.5(m(\bar{\chi}_{1}^{\pm})+m(\bar{\chi}_{1}^{0}))$	1501.07110 1708.07875 1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R},\tilde{\ell}{ ightarrow}\ell\tilde{\chi}_{\perp}^{0}$	$\begin{array}{c} 2\ e, \mu \\ 2\ e, \mu \end{array}$	0 ≥ 1	Yes Yes	36.1 36.1	$ ilde{\ell}$ 0.18	0.5			$m(\bar{\ell}_1^0)=0$ $m(\tilde{\ell})$ - $m(\bar{\ell}_1^0)=5$ GeV	1803.02762 1712.08119
	$\widetilde{H}\widetilde{H}$, $\widetilde{H}{ ightarrow}h\widetilde{G}/Z\widetilde{G}$	$\overset{0}{\text{4}}{e},\mu$	$\geq 3b$	Yes Yes	36.1 36.1	H		0.29-0.88		$BR(\tilde{\chi}^0_1 \to h\tilde{G}) = 1$ $BR(\tilde{\chi}^0_1 \to Z\tilde{G}) = 1$	1806.04030 1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$ \tilde{X}_{1}^{\pm} $ $ \tilde{X}_{1}^{\pm} $ 0.15	0.46			Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
	Stable \tilde{g} R-hadron Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}^0_1$ GMSB, $\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}^0_1$ $\tilde{g}\tilde{g}, \tilde{\chi}^0_1 \rightarrow eev/e\mu v/\mu\mu v$	SMP 2γ displ. $ee/e\mu/\mu_0$	- Multiple - u -	Yes	3.2 32.8 20.3 20.3	$egin{aligned} & & & & \\ & & & & \\ & & & & \\ & & & & $	0.44		1.6 1.6	2.4 $ m(\tilde{\chi}^0_1) = 100 \text{ GeV} $ $ 1 < r(\tilde{\chi}^0_1) < 3 \text{ ns, SPS8 model} $ $ 6 < cr(\tilde{\chi}^0_1) < 1000 \text{ mm, m}(\tilde{\chi}^0_1) = 1 \text{ TeV} $	1606.05129 1710.04901, 1604.04520 1409.5542 1504.05162
RPV	$ \begin{array}{c} LFV \; pp \!$	eμ,eτ,μτ 4 e, μ 0 4-	0 5 large- <i>R</i> j Multiple	- Yes ets -	3.2 36.1 36.1 36.1	$\begin{split} \tilde{Y}_{\tau} \\ \tilde{X}_{-}^{1} / \tilde{X}_{0}^{0} & [A_{i33} \neq 0, A_{12k} \neq 0] \\ \tilde{g} & [m_{i} \tilde{X}_{0}^{0}] = 200 \text{ GeV}, 1100 \text{ GeV}] \\ \tilde{\chi}_{12}^{u} = 2e \cdot 4, 2e \cdot 5] \end{split}$		0.82	1.9 1.33 1.3 1.9 5 2.0	λ'_{311} =0.11, $\lambda_{132/133/233}$ =0.07 $m(\tilde{\chi}^0_1)$ =100 GeV Large λ''_{112} $m(\tilde{\chi}^0_1)$ =200 GeV, bino-like	1607.08079 1804.03602 1804.03568 ATLAS-CONF-2018-003
	$\begin{split} \tilde{g}\tilde{g},\tilde{g}\to tbs/\tilde{g}\to t\tilde{k}_1^0,\tilde{\chi}_1^0\to tbs\\ \tilde{t}\tilde{t},\tilde{t}\to k\tilde{\chi}_1^0,\tilde{\chi}_1^0\to tbs\\ \tilde{t}_1\tilde{t}_1,\tilde{t}_1\to bs\\ \tilde{t}_1\tilde{t}_1,\tilde{t}_1\to b\ell \end{split}$	0 2 <i>e</i> ,μ	Multiple Multiple 2 jets + 2 i 2 b	b -	36.1 36.1 36.7 36.1	$ \tilde{g} = [A''_{333} = 1, 1e-2] $ $ \tilde{g} = [A''_{332} = 2e-4, 1e-2] $ $ \tilde{I}_1 = [qq, bs] $	0.55 0.42 0	1.05 .61	1.8 2.1 0.4-1.45	m($\tilde{\chi}_1^0$)=200 GeV, bino-like m($\tilde{\chi}_1^0$)=200 GeV, bino-like BR($\tilde{t}_1 \rightarrow be/b\mu$)>20%	ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 1710.07171 1710.05544
	a selection of the available ma			es or	1	0 ⁻¹	1 1			Mass scale [TeV]	

^{*}Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

25 October 2018 J. Gonski 26

2L Higgsino Search

- **Met** > 200 GeV → trigger
- $p_T(jet1)>200 \text{ GeV} \rightarrow ISR$
- $|\Delta \phi(\text{jet,Met})| > 1.0 \rightarrow \text{mis-measured Met}$
- **nJet(50 GeV)**=1,2 \rightarrow no jets expected from the signal
- bJet veto → ttbar background
- upper cut on lepton $p_T \rightarrow$ soft leptons in the final state;
- upper cut on $m_{II} \rightarrow$ small invariant masses expected;
- Met/Ht → good discrimination as seen in the Run-2 analysis;
- $\mathbf{m}\tau\tau \to Z\tau\tau$ background;

Making E_Tmiss with ISR

- With no other final state objects, LSPs are back to back, no E_Tmiss in event
- Require ISR jet: collimate LSPs, generate measurable E_Tmiss for trigger

